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# CT: the unexpected evolution of an imaging modality

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**Abstract** The evolution of CT can be characterized remarkably well by three phases of developments assigned to the 1970s, 1980s and 1990s. The first decade saw rapid innovations followed by a phase of consolidation and slow growth in the 1980s, and finally a third phase of very rapid development including spiral CT and multirow detectors in the 1990s. The evolution of technical developments during these first three decades is briefly reviewed. CT has reached a very high degree of maturity, mastering almost all clinical demands. The focus of this review is set on potential future developments and trends. Further doubling or multiplying of the numbers of slices acquired simultaneously cannot be expected to provide further essential innovations. New paradigms are required to advance the field. Future potential developments are outlined, including multisource, multidetector scanners for cardiac and dual-energy CT, new detector technologies, approaches to data handling and dose management.

**Keywords** CT · Spiral CT · Technology · Image quality · Dose

## The evolution of CT to date

X-ray computed tomography (CT) has undergone a number of development cycles (Fig. 1). In 1972, right after the presentation of the invention of CT by Sir Godfrey Hounsfield [1], a very rapid phase of development began with the introduction of the first through fourth generations of CT scanners. The third generation with rotating X-ray tube and rotating detector has prevailed over the fourth generation, which uses a stationary ring detector. At the peak of development in the first decade of CT about 20 manufacturers were active in research and development and offered their scanner models on the market. CT was hailed as one of the greatest inventions for radiology and the Nobel Prize was awarded to its inventor in 1979.

The 1980s brought fewer innovations than the preceding decade. New applications and refinements of the technology were the focus of interest: dynamic CT, quantitative CT for bone mineral measurement, dual-energy CT and high-resolution CT are respective examples. However, in general there were only a few spectacular developments. The concurrent advances in magnetic resonance imaging (MRI) and ultrasound led to the general prognosis that CT was "dead" and that it would soon be replaced by MRI. The importance of the introduction of slip ring technology in CT, which was developed for improvements in dynamic CT and allowed for continuous data acquisition, was not widely recognized at the time. The introduction of spiral CT in 1989 [2] received more recognition, but at the same time it also met with general scepticism. Experts doubted that this new approach to scanning would be able to provide adequate image quality.

The 1990s was again a decade of very rapid technical and clinical developments. Spiral CT not only became an immediate focus of research, but it was also integrated into clinical routine within a very short time. The possibility to scan organs and anatomical regions continuously within a very short time yielded convincing results, and the inherent advantages of the spiral scanning mode with respect to lesion detection [3] and to isotropic spa-

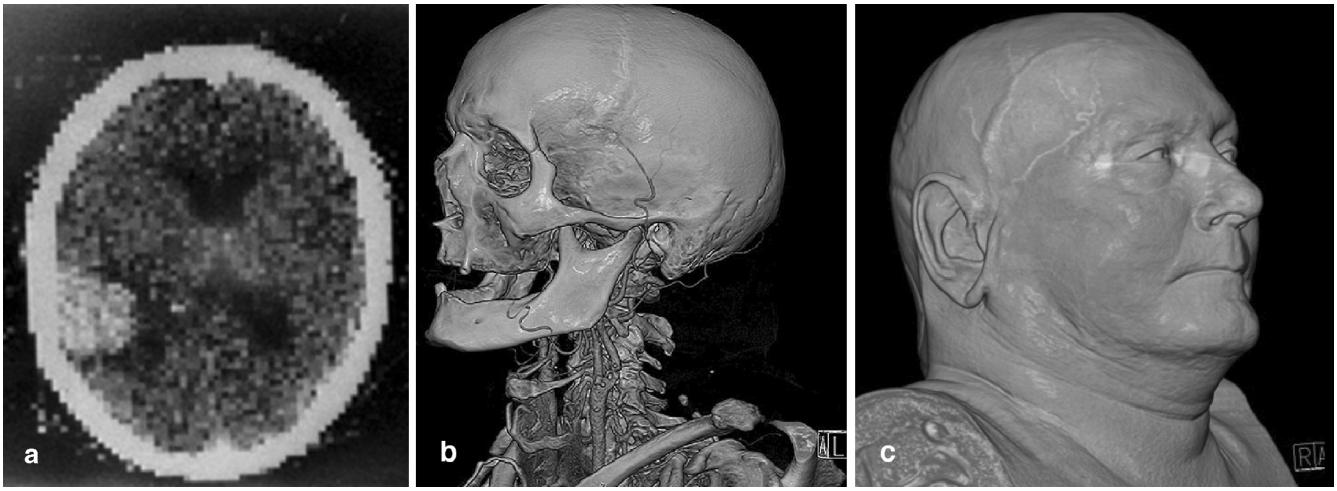

**Fig. 1** The evolution of CT over time is well documented by respective image examples. **a** The past: scanning of single anatomic slices, initially limited to the brain and to coarse matrices. **b** The present: fast scanning of volumes at high resolution enabling, for example, CT angiography. **c** The future: the image, derived from a 64-slice spiral scan, indicates scepticism, which is always appropriate when predictions are being made

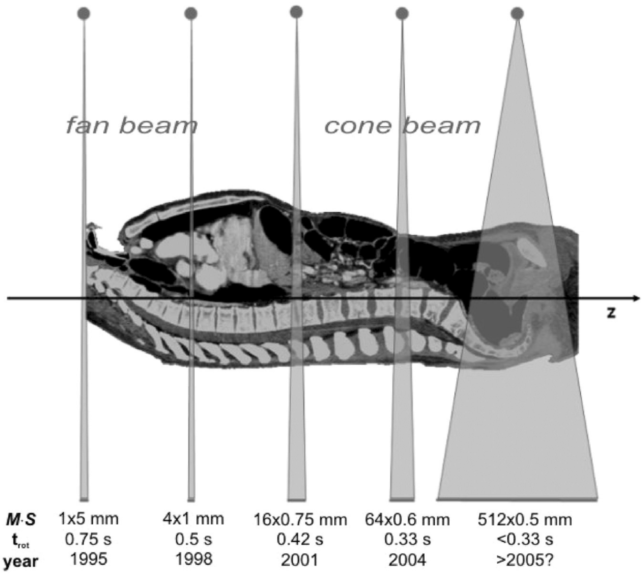

**Fig. 2** The evolution of modern CT is documented by the recent development of multirow detectors for spiral multislice scanning. CT went from scanning with a single-fan beam to multi-fan and cone beams. The imminent question is if this development will continue

tial resolution [4] were apparent. Yet, scanning with thin slices and the necessary X-ray power was not available at that time to allow satisfactory parameter settings for clinical routine. This shortcoming initiated the development of multirow detectors and thereby the introduction of multislice scanning modes and additional improvements in X-ray components providing higher power levels. The first generation of multislice CT (MSCT) scanners was introduced in 1998. New technology led to the introduction of several new advanced applications in the 1990s. A prime example is cardiac spiral CT based on retrospective phase-selective imaging of the heart in spiral scan modes [5–7]. Also the first PET/CT combination scanner was announced in 1999 [8]. The renaissance of CT, which was predicted in the first half of the 1990s, was fully realized by the end of the millennium.

The first 5 years of the new millennium showed continued and very impressive developments of both CT technology and applications. The second generation of multislice scanners was introduced in 2001, offering 16-slice acquisition simultaneously and 64-slice scans in 2004. The speed of development surprised and sometimes even irritated both experts and laymen. One of the pending questions is whether this development (Fig. 2) will simply continue. Does Moore's law which correctly predicted a doubling of computing power every 18 months, still apply to CT? Possible developments and trends for the coming years are presented and discussed in the next section.

## Continued evolution of CT in the future

A continuation of development seen in the early 2000s is certainly possible, in particular the detector technology would allow adding more detector rows. However, there are reasons which speak against it:

1. Cost will necessarily be higher.
2. There are disadvantages associated with extended cone beams with respect to image quality and the potential for dose optimization using tube current mod-

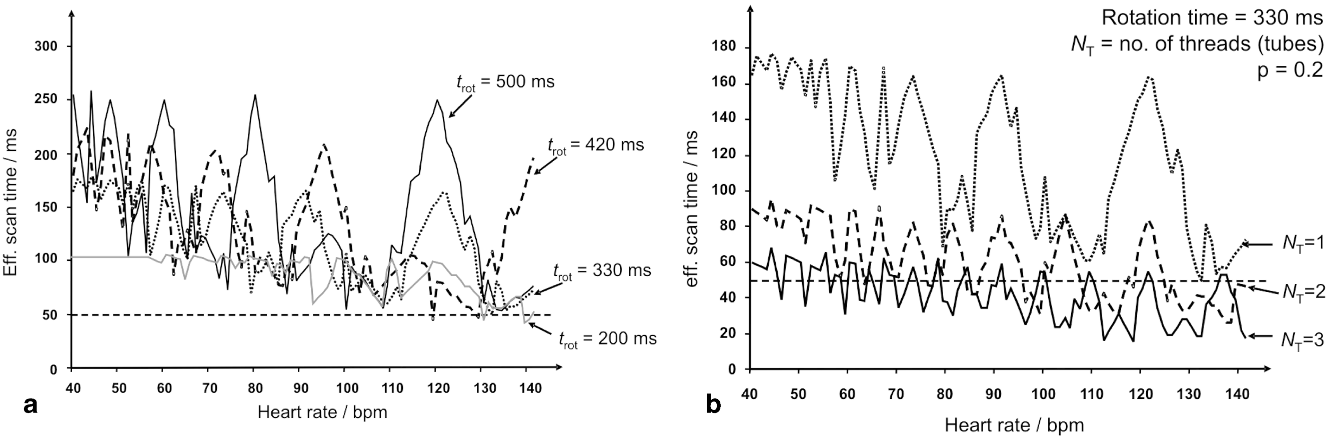

**Fig. 3** Cardiac CT demands further improvements in temporal resolution, with effective scan times of 50 ms or less and the necessary higher X-ray power defined here as the goal. Even for rotation times of 200 ms this is not achievable at all heart rates (**a**), but would be a good approximation with multiple tube-detector systems (**b**). See text for explanation

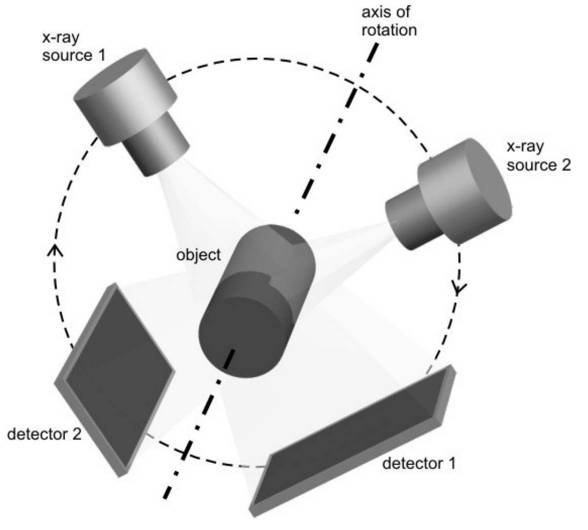

**Fig. 4** Scanner designs with multiple tube-detector systems will allow reducing scan times and providing increases in X-ray power. The micro-CT prototype design shown also aims to allow for dual-energy examinations and for higher dose efficiency. *Detector 1* provides a wide field of measurement, *detector 2* high z-coverage

ulation and automatic exposure control techniques [9].

3. Already today we have to limit the speed of acquisition in many cases since the high-performance scanners allow acquisition speeds which are higher than the speed at which the contrast medium bolus travels through the vascular bed.

In general, almost all clinical demands are met today. So, why should there be an extension of a costly detector which might be accompanied with potential disadvantages? Moore's law proved valid in CT for almost a decade, but this trend is unlikely to continue in the future. There is no disadvantage associated with increased computing power, but there would be if the number of detector rows increased indefinitely.

At present there are only few fields of applications which demand further technological developments: cardiac CT, where effective scan times of typically 50 ms are desired, and perfusion measurements, where scanning of larger organ anatomic ranges demands higher z-coverage. Interventional or intra-operative imaging constitutes a further demand, but this will most likely be covered by the use of flat-panel detectors employed in C-arm units and, although important in many respects, will not be covered further here as it does not affect the development of the typical clinical CT scanner under discussion.

Reduction of scan times has been the major goal of all developments since the beginning of CT. Decisive measures for imaging the heart included the reduction of the rotation time and the development of dedicated reconstruction algorithms for phase-selective heart imaging. The performance of such algorithms will depend on the interplay of the rotation frequency and of the heart frequency [6] (Fig. 3a). Today, effective scan times of typically 80 to 200 ms are achieved, which provides excellent image quality in the majority of clinical cases. However, in typically 10 to 20% of the cases examined not all segments of the coronary artery tree are diagnosable. Effective scan times of about 50 ms are expected to resolve this problem. It is not easy, however, to achieve this technically.

A respective reduction of rotation times is problematic. This is not only due to mechanical constraints and the respective increases of centrifugal forces beyond about 30 *g* which we are facing today already. It is above all due to the increased demand on the X-ray power, which has to be increased inversely to the rotation time to pro-

**Table 1** Performance characteristics[a] of CT in a comparison from 1974 to 2004

| | 1974 | 1984 | 1994 | 2004 |
|---|---|---|---|---|
| Minimum scan time | 300 s | 5–10 s | 1–2 s | 0.33–0.5 s |
| Data per 360° scan | 57.6 kB | 1 MB | 1–2 MB | 10–100 MB |
| Data per spiral scan | – | – | 24–48 MB | 200–4000 MB |
| Image matrix | 80 × 80 | 256 × 256 | 512 × 512 | 512 × 512 |
| Power | 2 kW | 10 kW | 40 kW | 60–80 kW |
| Slice thickness | 13 mm | 2–10 mm | 1–10 mm | 0.5–1 mm |
| Spatial resolution | 3 Lp/cm | 8–12 Lp/cm | 10–15 Lp/cm | 12–25 Lp/cm |
| Contrast resolution | 5 mm/5 HU/ 50 mGy | 3 mm/3 HU/ 30 mGy | 3 mm/3 HU/ 30 mGy | 3 mm/3 HU/ 30 mGy |

[a] Typical values for high performance scanners

vide the necessary X-ray intensities in the reduced time frame. Technical developments to provide generators and X-ray tubes operating at up to 200 kW, i.e., twice the power levels available today, are problematic. A favourable approach may be to add more X-ray sources and detectors to the rotating gantry. This approach is not all that new; it was already suggested in the 1970s [10]. Scan times will be reduced proportionally to the number of systems employed. The effect on effective scan times for cardiac CT as a function of heart rate is depicted in Figure 3b. The use of two tube and detector combinations may be the optimum with respect to balance of cost and benefit for a rotation time of about 300 ms.

Having more than one source available would also allow looking into new CT applications. Dual-energy CT, which has suffered from technical limitations to date, would become possible in technically adequate form for the first time. A design for use in small-animal micro-CT imaging is shown in Figure 4. Respective developments still have a significant potential for clinical CT, in particular when new tracers become available such as higher atomic number contrast media which lend themselves to material-selective dual-energy imaging.

For sustained innovation and for the long-term future of CT it will be important to extend the range of applications and to offer more than just images depicting Hounsfield units. To "escape from the HU cage" is a declared goal. Perfusion imaging [11] is one example which has already become clinical reality. PET/CT combination imaging is now established in clinical routine [8, 12]. More examples for functional imaging can be expected and would strengthen the continued growth of the modality.

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